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ITER Asymmetric Error Fields and Their Correction*

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Abstract — The locked mode threshold as a consequence of asymmetric error fields is expected to be an order of magnitude more stringent in ITER than in present tokamaks. Analysis is presented which summarizes the error field sources expected in ITER. A statistical approach is developed which combines the PF and TF sources into a single multi-mode predictor. A non-linear optimization technique is used to evaluate performance of the proposed error field correction coil system on the expected error field sources. The system is shown capable of correcting the expected residual machine error fields to below the predicted locked mode threshold.

I. INTRODUCTION

Locked mode phenomena in present tokamak devices can lead to performance degradation and premature discharge termination [1]. Recent tokamak experiments [1-4] combined with theoretical models [1,5] have shown that non-axisymmetric fields (asymmetric error fields) in tokamaks interact with the plasma on rational q surfaces to form magnetic islands. Normally these islands are dissipated by the natural plasma rotation and by neutral beam induced rotation. However, error fields above a threshold size, referred to as the Locked Mode Threshold (LMT), produces sufficient torque to stop plasma rotation. Once the mode locks in the lab frame, the self healing properties of rotation are lost and the static error fields are amplified. This can lead to loss of performance and ultimately, plasma disruption [6]. As a consequence, asymmetric error field reduction s a major design challenge for new machines [7].

II. MODELS AND ITER LIMITS

Similar error field models were independently developed by ITER home teams in Europe, the Former Soviet Union and the United States. Standard magnetic analysis techniques are used to determine the normal magnetic field component on rational q surfaces (safety factor, q = 1, 2, 3). Asymmetric error fields are characterized by decomposition of this normal component on rational surfaces in terms of poloidal (m) and toroidal (n) helical harmonics and are typically referred to as m,n error fields. Fourier analysis following unperturbed field lines is used to define the m,n magnetic field components:

$$B_{m,n} = \frac{1}{2\pi^2} \int_{\phi=0}^{\phi=2\pi} \left[\int_{\hat{\theta}=0}^{\hat{\theta}=2\pi} B_{\perp}\left(\phi,\hat{\theta}\right) e^{\, i\left(n\phi - m\hat{\theta}\right)} d\hat{\theta} \right] d\phi \qquad (1)$$

where $B_{m,n}$ is the m,n helical component, ϕ is the toroidal angle, $B_{\perp}$ is the magnetic field perpendicular to the unperturbed flux surface and $\hat{\theta}$ is the modified poloidal angle given by:

$$\hat{\theta}(l) = \frac{1}{q} \int_{l_o}^{l} \frac{B_{\phi}}{R\,B_p} dl \quad . \qquad (2)$$

B_{ϕ} and B_p are the unperturbed toroidal and poloidal magnetic fields, respectively; R is the major radius, l is the poloidal length along the q surface and l_o is the initial value of l corresponding to $\hat{\theta} = 0$. The rational q surface is given by:

$$q = \frac{1}{2\pi} \oint \frac{B_{\phi}}{RB_p} dl = \frac{m}{n} \qquad (3)$$

Error field limits have been established for ITER based on scaling of the LMT in present experiments and are shown in Fig. 1. Limits decrease with increasing machine size owing to the slower natural rotation of larger machines. Lower order error fields, especially m,n = 2,1, are the most troublesome for low q tokamak operation. The solid line shows an early estimate of the 2,1 LMT for different devices without including the impact of other modes [6]. This projects to an ITER 2,1 limit of:

$$B_{21} \big/ B_{\phi o} \le 1 \times 10^{-5} \equiv 1 \;\; \underline{\text{Unit}} \qquad (4)$$

where $B_{\phi o}$ is 5.7 T, the central toroidal field in ITER.

Although the 2,1 mode typically is the most dangerous, recent experiments have shown that other lower order (m,n) modes, most notably the 1,1 and 3,1, exhibit a drag effect on the q=2 surface. A more general expression including this influence, based on DIII–D scaling is [6]:

$$B_{3-\text{mode}} \equiv \sqrt{B_{2,1}^{1} + 0.8B_{3,1}^{2} + 0.2B_{1,1}^{2}} \le 2 \times 10^{-5} B_{\phi o} \qquad (5)$$

The dotted line in Fig. 1 shows this more general formulation,

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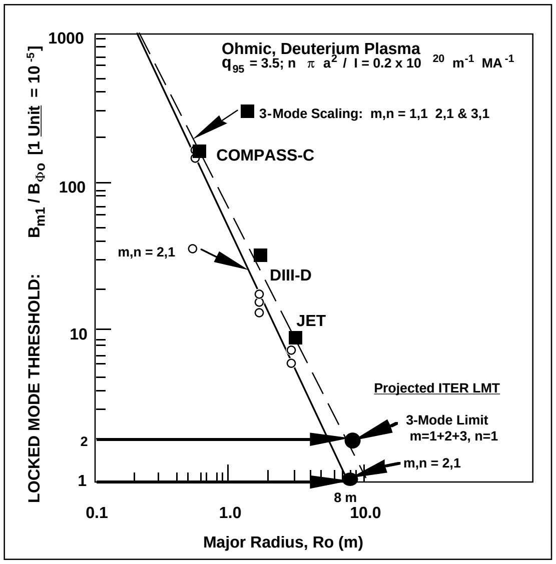

Fig. 1. Scaling of the LMT for Ohmic plasma based on experiments in COMPASS-C, DIII-D and JET. Solid line is LMT for m,n = 2,1 mode and the dashed line is for the 3-mode limit given in (5) [7].

recent experiments on JET and COMPASS-D have shown similar results [8]. Equation (5) represents the primary design constraint being imposed on ITER error fields.

III. ERROR FIELD SOURCES

The primary source of error fields in existing machines is misalignment of the toroidal and poloidal field coils (TF & PF). Similar results are expected for ITER. The PF and TF coil contributions have been determined based on a statistical combination of individual error fields from misalignment errors expected during machine construction and assembly. The position errors are assumed to be independent random variables with standard deviation given by tolerance and assembly studies. As an example, each PF coil has two rigid body degrees of freedom (radial displacement and tilt) that contribute to the asymmetric error field. For each of these displacements there are two independent random variables, one each in the X and Y directions. In all, the 10 PF coils produce 40 random variables associated with the radial and tilt displacements of each coil. Higher order displacements such as coil ellipticity and warpage contribute primarily to the n=2 modes and are not included in the present analysis.

The probability of an error field lying between B_{min} and B_{max} can be expressed in terms of a probability density function:

$$P\left\{B_{min} \le B_{mn} \le B_{max}\right\} = \int_{B_{min}}^{B_{max}} f_{Bmn}\left(B_{mn}\right) d B_{mn} \qquad (6)$$

The displacement to error field relation is linear allowing calculation of the probability density function as a Rayleigh distribution:

$$f_{B_{mn}}\left(B_{mn}\right) = \frac{B_{mn}}{\sigma^2_{B_{mn}}} e^{-\frac{B_{mn}^2}{2\sigma^2_{B_{mn}}}} U(B_{mn}) \qquad (7)$$

where, σ_{Bmn} is the square root of the sum of the squares of the individual m,n components. Each individual component is made up of the manufacturing and assembly tolerance multiplied by the m,n error field associated with a unit displacement in this direction. U is the unit step function. A similar expression can be developed for the 3-mode formula and is expressed as the “Weighted” Rayleigh distribution:

$$f_{B_{3-mode}}\left(B_{3-mode}\right) = 2\, B_{3-mode} \left[\prod_{m=1,3} \alpha_{m1}\right] \left[\sum_{m=1,3} \frac{e^{-\alpha_{m1} B^2_{3-mode}}}{\prod_{\substack{k=1,3 \\ (k\neq m)}} (\alpha_{k1} - \alpha_{m1})}\right] U(B_{3-mode}) \qquad (8)$$

where:

$$\alpha_{m1} = \frac{1}{2\, W_{m1}\, \sigma^2_{B_{m1}}} \qquad (9)$$

and W_{m1} are the weights of the 1,1; 2,1 and 3,1 modes in the 3-mode formula (5): 0.2, 1.0, and 0.8.

Fig. 2 shows the B_{21} and $B_{3\text{-mode}}$ probability density function for misalignment of the PF coils at the start-of-flattop (SOF) current state. The SOF state is used as a baseline because low plasma density and lack of rotation from neutral beams at that time makes the plasma vulnerable to locked modes. The cumulative percentile points shown in the figure represent fractional accumulated area under the curve and define the percent probability that ITER will be below a particular error field level. Table I shows important statistical properties of the 2,1 and 3-mode distributions. The most probable value represents the peak in the curves of Fig. 1. The 50th percentile represents the expected level of error field. The 99.9th percentile represents a “worst case” limit. A similar study was performed which included both the PF and TF coils in the analysis. The results are shown in the last column of the table and indicate that the combined coil set is expected to produce 7.3 Units of 3-mode error field.

Table I
Error field probability density distribution statistics for misalignment of the PF & TF coils at the SOF current state

Statistic 1 Unit = 10^{-5}	$B_{21}/B_{\phi o}$ PF [Unit]	$B_{3\text{-mode}}/B_{\phi o}$ PF [Unit]	$B_{3\text{-mode}}/B_{\phi o}$ PF&TF [Unit]
ITER LMT Limit	1	2	2
Most Probable	1.8	2.9	6.8
50th Percentile	2.1	3.1	7.3
99.9th Percentile	6.7	7.1	16.6

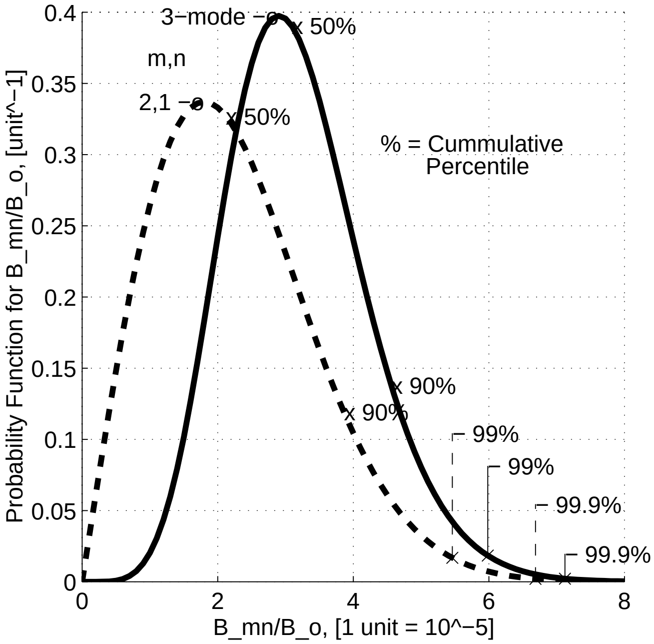

Fig. 2. Probability density distribution for the 2,1 and 3-mode error fields from radial and tilt misalignment of the PF coils at the SOF current state.

In addition to the major coil contributions, the low error field limits in ITER requires the investigation of other error field sources. Table II presents a summary of potential sources and an estimate of the 3-mode error field from each source. Most sources are small compared to the PF and TF contributions.

IV. CORRECTION COIL SYSTEM

Based on the *a posteriori* knowledge of LMT limits in ITER, stringent requirements are being placed on coil manufacturing and assembly tolerances and great care is being devoted toward exploring a wide range of error field sources. However, the residual error field is still expected to be 5 to 8 times the LMT limit. Fig. 3 shows a set of correction coils (CC) which are being implemented in the design to reduce the residual levels to below the LMT. The system is composed of three poloidally distributed sets of superconducting coils designated: Top, Side and Bottom. The top and bottom coil sets each contain four individual coils; toroidally opposite coils within each set are connected electrically in anti-series within the cryostat to allow for correction of only the n=1 mode. The side coil contains eight individual coils and two adjacent coils are connected in series with each toroidally opposite pair connected in anti-series. Each coil set has two independent power supplies which allows adjustment of the toroidal angle of error field. The complete system utilizes six power supplies providing the capability of zeroing three modes of n=1 error field exactly. The CC current limits for the Top, Side and Bottom sets are: 45, 150 and 240 kA-t, respectively, and are based on structural and performance properties of the systems.

Table II
Potential asymmetric error field sources and estimates of their magnitudes

Error Field Source	3-mode magnitude 1 Unit = 10^{-5}
PF & TF coil misalignment errors	7.3 Units
PF coil shape errors	<< 1 Unit
Coil internal connections & buswork	< 1 Unit
Eddy currents	<< 1 Unit
TF ripple ferromagnetic inserts	<< 1 Unit
Test blanket ferromagnetic elements	< 1 Unit
Neutral beam magnetic shield$^{\pm}$	< 1 Unit
Other sources: cryogenic & stress distortions, building ferromagnetic, earth's magnetic field	to be evaluated

$^{\pm}$Blanket shield is actively corrected

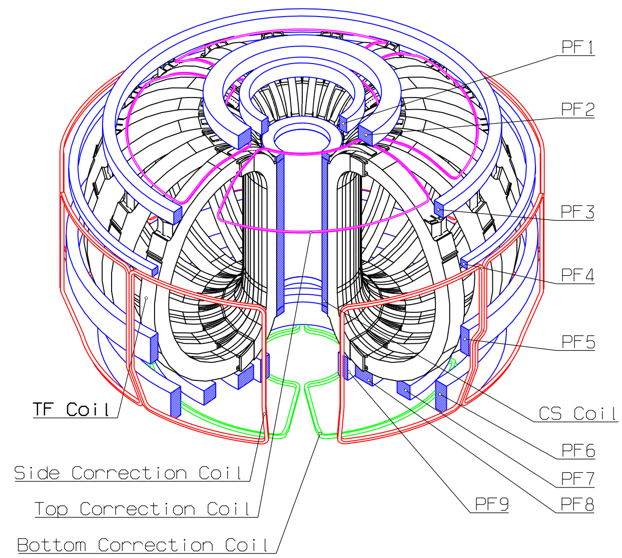

Fig. 3. ITER geometry showing major coil systems including the three CC sets: Top, Side and Bottom.

A non-linear, least square constrained minimization procedure is utilized to optimize the performance of the overall correction coil system. The performance of the CC is evaluated based on its capability to reduce or eliminate error field magnitude and phase representative of sources expected in the machine for m,n components 1,1; 2,1 and 3,1 in accordance with the 3-mode formula (5). In particular, a single PF coil is used as an error field source and the correction coil currents are optimized to reduce the associated error field to below the LMT. This optimization is performed with constraints prescribed by the coil current limits.

Fig. 4 shows the performance of the CC system on error field spectra typical of the PF coil. Shown is the residual machine 3-mode error field associated with radial shifts of individual PF coils that can be corrected to below the 2 Unit LMT limit with the CCs at or below their respective current limits. The relative magnitude and phase are prescribed by the particular PF coils radial shift; only the absolute magnitude of the error field is adjusted to determine the CC capability. Very similar results are seen if PF tilts are used as the input error fields

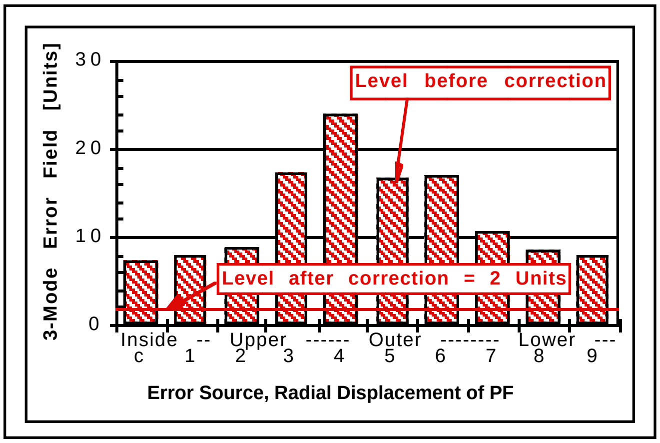

Fig. 4. Level of error field correctable to the LMT limit with the CC at or below their current limits and with error field spectra typical of that from individual PF coils.

rather than radial displacements. As shown in the figure, the CC is best at eliminating errors with spectra that originates from misalignments of outer coils and is worst at correcting error fields originating from misalignments near the center of the machine. Essentially, the CC system is capable of correcting approximately 20 Units of 3-mode error field to below the 2 Unit LMT if the error field spectra is typical of that produced by misalignment of the outer coils.

Fig. 5 shows the CC currents required to correct the error fields shown in Fig. 4. The bottom coil requires the largest current owing to its large plasma-to-coil separation and small poloidal extent. The top coil is located inside the PF coils and is the most efficient CC set. It is also a single turn conductor and has restrictive current carrying capability. After factoring in the relative efficiency of the different CC sets, the coil current requirements follow the source location. That is, errors from misalignment of the top coil are best corrected by, and require larger current relative to its limit in, the top correction coil.

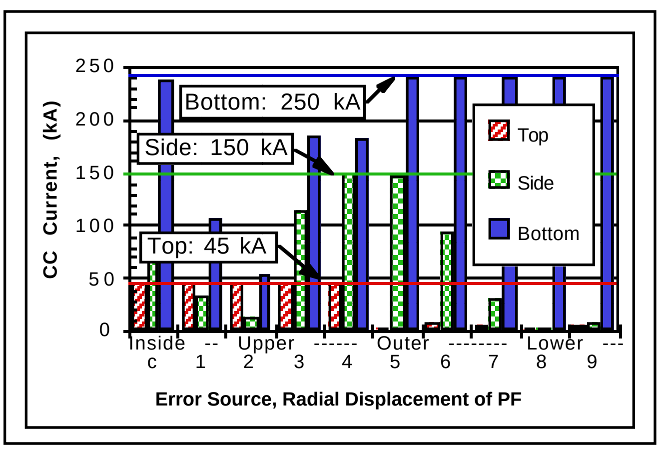

Fig. 5. CC current required to reduce PF coil target error field magnitudes shown in fig. 4 to below the LMT.

The statistical approach used in the previous section can be extended to establish a target error field spectrum associated with a combination of all PF coil shifts and tilts. The performance of the CC system can then be evaluated for reducing this target error field. Based on the statistically most probable spectra, the CC is capable of correcting approximately 15 Units of 3-mode error field to the LMT limit. This capability is approximately 5 times the level expected from the PF coil and twice the level expected from the combined PF/TF coils (7.3 Units). Currents required for the Top, Side and Bottom coils are 26, 145 and 240 kA-t, respectively. The Side and Bottom CC's are at or near their respective current limits and the top coil is within approximately 60% of its limit, showing that the coil capabilities are well matched with the anticipated error field spectra.

V. CONCLUSIONS

Asymmetric error field limits in ITER have been established based on scaling of the LMT from present experiments. The 3-mode LMT limit for ITER is 2 Units which is a factor of 5 less than that experienced in present machines. Accordingly, great attention is being devoted toward identifying and reducing potential error field sources in ITER. PF and TF coil misalignment errors are expected to be the largest error field sources. Based on a statistical combination their expected level is 7.3 Units. Other sources are shown to each produce less than 1 Unit. A correction coil system consisting of 3 independent, poloidally distributed coil sets is being designed to reduce the residual error field to below the LMT. This CC system has a factor of 2 capability over the statistically expected PF/TF error field based on typical modal spectra.

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